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UPGRADED MOD I STIRLING ENGINE FOR AN AIR FORCE VAN INSTALLATION

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ABSTRACT

The Automotive Stirling Engine (ASE) program is directed at the development of the kinematic Stirling engine for automotive use. The program is sponsored by the Department of Energy (DOE) and managed by the NASA-Lewis Research Center. The suitability of the engine for transportation applications other than passenger cars is also being pursued. One example is the installation of the Stirling engine in an Air Force van used for flight line duty. This van program is jointly sponsored by the NASA Technology Utilization Office and DOE. The intent is to demonstrate the potential for improved fuel economy and fuel flexibility, concentrating primarily on the use of JP-4 fuel.

This paper describes the installation of the Mod I Stirling engine in the van, including checkout of the system on a vehicle dynamometer, as well as engine performance in over-the-road driving tests. Engine characterization on an engine dynamometer test stand and comparison of predicted vehicle performance with the vehicle dynamometer results are discussed. Performance of the engine on unleaded gasoline and JP-4 is presented. Development of the combustion system for operation on gasoline, JP-4, or diesel without changes is also documented.

INTRODUCTION

The Automotive Stirling Engine (ASE) program was initiated in 1978 with the objective of developing a Stirling engine for automotive use.(1) The primary features sought were

- Fuel economy improved by 30% over current spark-ignition (SI) engines
- Acceleration comparable to an SI engine installed in the same vehicle
- Emissions meeting proposed 1985 Federal standards
- Weight and cost comparable to competitive engines
- Capability for multifuel operation.

The program was initiated by adapting a stationary Stirling engine (P-40) to an automotive installation to demonstrate the feasibility of the Stirling engine in this application. The engine functioned acceptably in the initial installation; however, it was too heavy and did not provide improved fuel economy or adequate acceleration.

A series of engine designs followed the initial installation, leading to the development of an engine to meet the program goals. The MOD I engine, the first engine designed specifically for the automotive application, (2) included the following features.

- Part-power optimization for improved fuel economy at the low power levels typical of the automotive driving cycle
- Higher power density for improved performance.

An upgrade to that engine, the Upgraded Mod I, provided an evolutionary modification to the Mod I design. The improvements made in the Upgraded Mod I that further demonstrated the potential capability of the Stirling engine were (3)

- Increased part-power optimization for fuel economy
- Reduction in strategic materials for lower production cost
- Design modifications for lower weight
- Increased set temperature for higher power density
- Control system modifications for improved transient response.

Performance and fuel economy progress made in the ASE program to date is shown in Figure 1. From a deficit of 20% in fuel economy and a 0 to 60 mph acceleration of 34 seconds, the current Upgraded Mod I provides a fuel economy improvement of 14%, compared to spark ignition vehicles. In addition, acceleration of 15 seconds was achieved, which compares well with spark ignition engines. Figure 1 also shows the predicted values for the Mod II engine, the final automotive design, which is currently in initial development.(4, 5). Figure 2 shows the Mod II engine configuration.

Although unleaded gasoline, the primary fuel by definition, was used throughout most of the engine development, the multifuel capability of the Stirling engine has been demonstrated, both under the ASE (6) program and a related DOE-sponsored program (7). Table 1 lists MTI's experience with several fuels in the automotive engine. Among these are gasohol and diesel, which are two of the four fuels designated by DOE for the ASE program. The remaining two fuels, kerosene and home heating oil, are similar to diesel. Hence, testing of all three fuels was considered unnecessary. Although a wide range of fuels

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was tested, evaluation was limited to steady-state performance or brief vehicle demonstrations. The key question of transient vehicle operation, including start-up capability and durability/reliability, was not addressed.

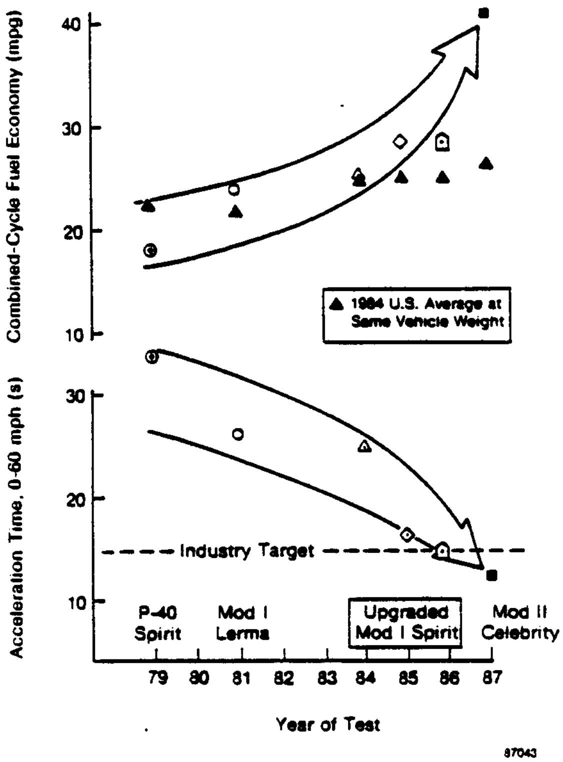

Fig. 1 ASE Vehicle Performance Progress

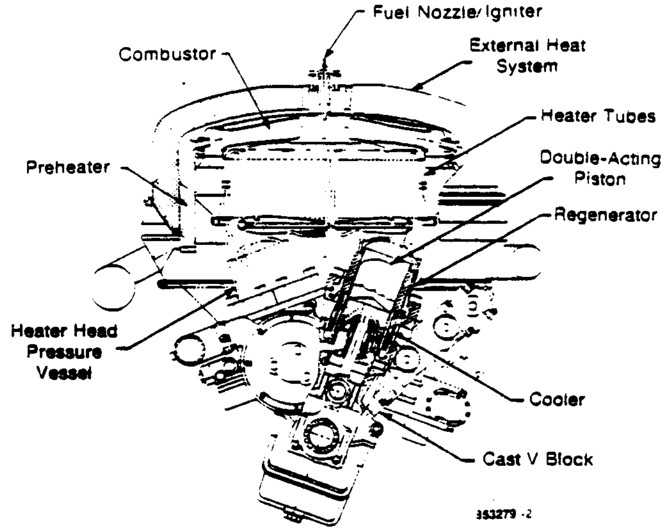

Fig. 2 Mod II Configuration, Including External Heat System

THE AIR FORCE VAN APPLICATION

The Air Force uses vans (Figure 3) to transport maintenance personnel to and from the flight lines (8). The vehicles operate continuously when there is flight activity. Often, the vehicle is parked at the flight line waiting either for personnel to complete service on an aircraft or for a call to proceed to another location. Typically, the engine remains running during the parked periods, operating at idle. The duty cycle then consists of short-duration trips interspersed with considerable amounts of engine idle time. The flight line speed limit is 25 mph; therefore, vehicle acceleration and high-speed capability are of secondary importance.

Table 1

MTI ASE Alternative Fuels Experience

Engine	Output (kW)	Application	Fuel	Date(s)	Rig[1]	Engine	Vehicle
P-40	40	Automotive	Gasoline[2]	1978-81	X	X	X
			Ethanol	1980			X
			Gasohol	1981		X	
			ERBS[3]	1981		X	
			Diesel (DF-2)	1980-81		X	X
			Shale Oil[4]	1981		X	
Mod I and Upgraded Mod I	58	Automotive	Gasoline[2]	1981-85	X	X	X
			Diesel (DF-2)	1983-84	X	X	X
			JP-4	1984		X	
			Naphtha	1983-84	X		
			Ethanol	1983-84	X		
			Methanol	1983-84	X		
			Diesel/ Naphtha[5]	1983-84	X		

NOTES:

[1]Combustion rig simulating the engine external heat system
[2]Design fuel
[3]"Experimental referee-broadened-specification" aircraft jet fuel
[4]Marine diesel fuel derived from shale oil
[5]50/50 blend

Fig. 3 Air Force Multistop Van

The standard Air Force van is powered by a 145-hp diesel engine. The Upgraded Mod I engine, sized for the passenger car application, produces approximately 75 hp, half that of the baseline engine. Since vehicle performance (speed and acceleration) is of secondary importance, the use of the lower power Stirling engine was considered acceptable to demonstrate concept feasibility in this application. A comparison of the vehicle performance with diesel and Stirling engines, as predicted by MTI's vehicle code, is shown in Table 2.

The key requirements for the van installation in Phase I of the program are reliability, improved fuel economy, and multifuel capability. The primary fuels of interest to the Air Force for flight line vehicle application are JP-4 and diesel. Currently, JP-4 is used in the aircraft, and diesel fuel is used in the flight line vans. A major advantage of the Stirling engine is that it can operate on a variety of fuels without modification of the engine or a decrease in performance. Operation of the vehicles on JP-4 would provide the potential for elimination of the diesel fuel supply system, which would be a major logistical benefit.

To fully demonstrate the ability of the Stirling engine to operate on JP-4, contaminated JP-4 and other fuels, and to demonstrate performance equivalent to current vehicles, a multiphase program has been formulated, as shown in Figure 4. The initial phase consists of converting the van to Stirling power and operating it for 500 hours on unleaded gasoline. The second part of Phase I will demonstrate operation for 500 hours on JP-4. Follow-on efforts would also incorporate diesel fuel. Phase II of the program will demonstrate operation in climatic extremes with the Upgraded Mod I engine installed in a vehicle more closely matched to the engine's power level in order to also demonstrate vehicle performance matching the baseline vehicle. In the third phase of the program, the ASE Mod II engine will be installed in an Air Force vehicle to demonstrate its readiness.

Table 2

Air Force Van Performance Predictions Using Vehicle Simulation Code

	Diesel	Stirling
Acceleration	145 hp	75 hp
0% Grade; 6,550 lb		
0-30 mph (sec)	4.8	10.5
0-50 mph (sec)	14.1	38.2
0-60 mph (sec)	20.7	--
0% Grade; 11,550 lb		
0-30 mph	7.9	18.9
30% Grade; 6,550 lb		
0-5 mph (sec)	1.3	12.5
Maximum Speed (mph)	21.4	5.8

NOTE: 4.10 Axle Ratio

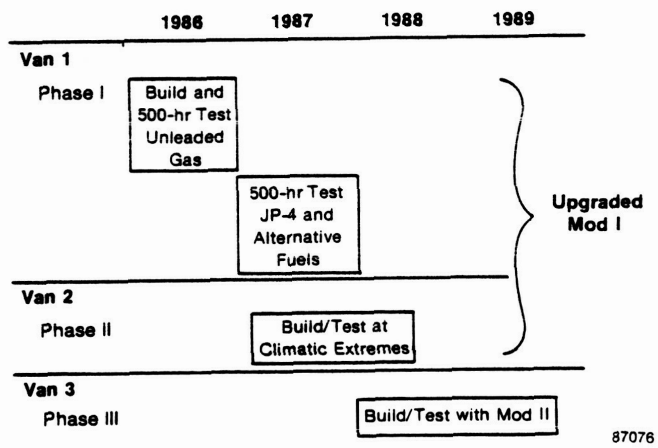

Fig. 4 Air Force Van Stirling Engine Demonstration Program

THE EFFECT OF FUEL PROPERTIES ON THE STIRLING ENGINE

One advantage of the Stirling engine is that fuel properties such as cetane and octane numbers, which denote auto ignition limitations of diesel and spark-ignition engines, are irrelevant. Stirling engine combustion occurs continuously at near-atmospheric pressure in an external heat system (EHS). This feature provides an inherent advantage over pressurized, intermittent combustion processes for minimizing NO_x and soot emissions, (9, 10) as well as for multifuel capability. The fact that combustion is separate from the internal working cycle allows not only greater fuel flexibility (solid, liquid, or gas) but also ready utilization of noncombustion heat input.

As related to the Stirling engine, the liquid fuel properties of most concern are heating value, flame temperature, viscosity, hydrocarbon composition, and the amount of nitrogen and sulfur. In order to ensure complete and environmentally acceptable combustion, fuel and air are mixed in slightly lean proportions. Excess air, typically 15-25%, is provided by an air/fuel control system to compensate for less-than-perfect mixing in the combustor. The exact proportion of the air and fuel required is a function of the fuel hydrogen/carbon ratio.

Thus, in order to maintain the same stoichiometry with different fuels, the controls must be modified, unless the fuels have similar hydrogen/carbon ratios. This ratio, along with flame temperature, influences the amount of heat transferred to the working gas and EHS blower power requirements (which in turn affects engine efficiency). The heating value determines the amount of EHS flow and, therefore, the size of the system. The remaining properties influence both exhaust emissions and durability, as shown on Table 3.

Table 3

The Effect of Liquid Fuel Properties on the Environment and Engine Durability

Property	Emissions	Durability
Nitrogen	NO_x Emissions	None
Sulfur	NO_x Emissions	Preheater Corrosion
Aromatics	Soot Emissions	Combustor Oxidation (Increased Luminosity)
Viscosity	Soot, CO, HC Emissions	None

A comparison of the typical properties of the Air Force van fuels (Table 4) indicates similar heating values and hydrogen-to-carbon ratios (flame temperatures). Thus, it was anticipated that a single combustion and air/fuel control system could be used for all three fuels. The increased viscosity of diesel fuel (over gasoline) at high ambient temperature is not of concern. However, on cold days, the diesel fuel may require heating. Engine preheater corrosion from sulfuric acid was not addressed because of the constraint to use existing engine hardware. A materials change from 310 SS would be needed for long-term (>1000 hr) operation on diesel fuel.

MULTIFUEL DEVELOPMENT

Although unleaded gasoline was used as a baseline, a program goal was to test the engine using JP-4 in the hope that only minor, if any, modifications would be required. The use of diesel fuel was considered a longer term goal. Targets set in order to measure the success of multifuel capability were

1. Heater head circumferential temperature variation $\leq 100°C$ to promote extended heater head life and to avoid an adverse effect on engine efficiency
2. Soot emissions ≤ 10, SAE/EPA smoke number, to ensure an invisible exhaust plume and to avoid preheater plugging
3. Start-up on gasoline and JP-4; diesel start-up to be evaluated later
4. Combustion efficiency, as indicated by CO and HC emissions, comparable to gasoline
5. Equal engine performance using JP-4 and gasoline.

In the Stirling engine, the combustor, the fuel nozzle, and the air/fuel control are the components having the most influence on the performance of the engine when testing a variety of fuels. A turbulator combustor that was extensively developed for automotive use with exhaust gas recirculation (11) was selected for use in the van. The fuel nozzle that was developed under the ASE program and designed especially to accommodate various fuels (12) was also applied to the van program. As shown in Figure 5, the nozzle is a three-hole, externally mixed air-assist design used with both gasoline and diesel fuels. It has demonstrated consistent nonplugging operation, even in the high-temperature environment in which it must function, i.e., 700 to 800°C combustor inlet air temperature.

The air/fuel control is a modified automotive Bosch K-Jetronic device. Its use is not optimal in that it is a volumetric device that affects van performance in two ways. Since the air/fuel ratio is leaner at lower fuel flows, engine efficiency is reduced due to the power required to provide the extra air needed for the lean mixture. Also, the difference in fuel density between gasoline and JP-4 causes the air/fuel ratio to be different for the two fuels. When air/fuel ratios are set to provide acceptable combustion properties with JP-4, the resultant leaner mixture with gasoline results in an engine efficiency penalty, again due to blower power requirements. See Figure 6. It is planned to replace the volumetric K-Jetronic device with a digital mass-based device in the third phase of the program. A control that operates on fuel mass instead of volume allows a constant air/fuel ratio with fuel flow, as well as identical ratios for gasoline, JP-4, and diesel fuels. No adjustment of the controller is needed when changing from one fuel to another.

Table 4

Air Force Van Fuel Properties

	Unleaded Gasoline	JP-4	Winter Grade Diesel
Distillation (°C)			
IBP/5%	29/41	62/74	119/180
10%/20%	46/57	80/91	199/219
30%/40%	69/84	106/134	230/240
50%/60%	102/119	166/188	253/264
70%/80%	136/152	196/204	277/293
90%/95%	172/193	216/227	313/330
EP	206	247	342
Hydrocarbon Type (% Vol.)			
Saturates	60.6	85.7	70.4
Olefins	12.3	2.3	1.9
Aromatics	27.1	12.0	27.7
Sulfur (%)	0.04	<0.005	0.17
API Gravity at 60°F	58.2	45.7	35.7
Flash Point (°F)	--	--	92
Viscosity at 100°F (cs)	0.50	--	2.43
Ramsbottom Carbon on 10% Residuum (%)	--	--	0.17
Ash (%)	--	--	0.0000
Water and Sediment (% Vol.)	--	--	<0.005
Carbon (%)	86.14	85.41	86.52
Hydrogen (%)	13.35	14.14	13.24
Heating Value (Btu/lb)			
Gross	19,770	20,089	--
Net	18,552	18,799	--
Reid Vapor Pressure (psi)	--	2.9	--

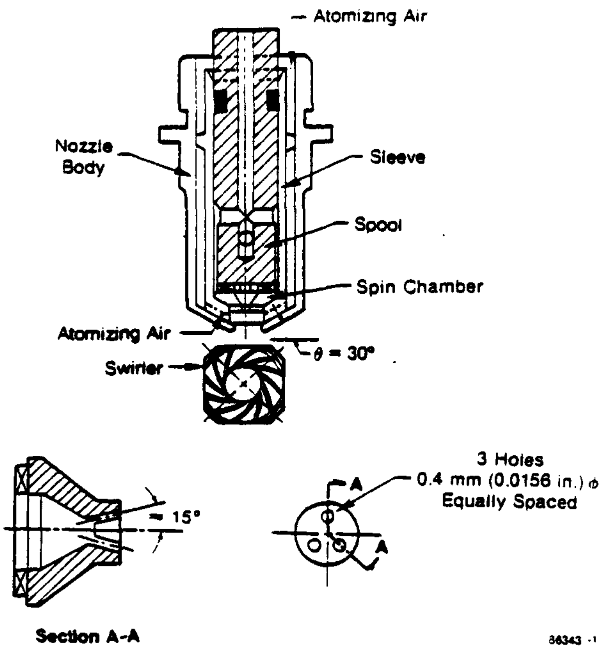

Fig. 5 Three-Hole Conical Fuel Nozzle

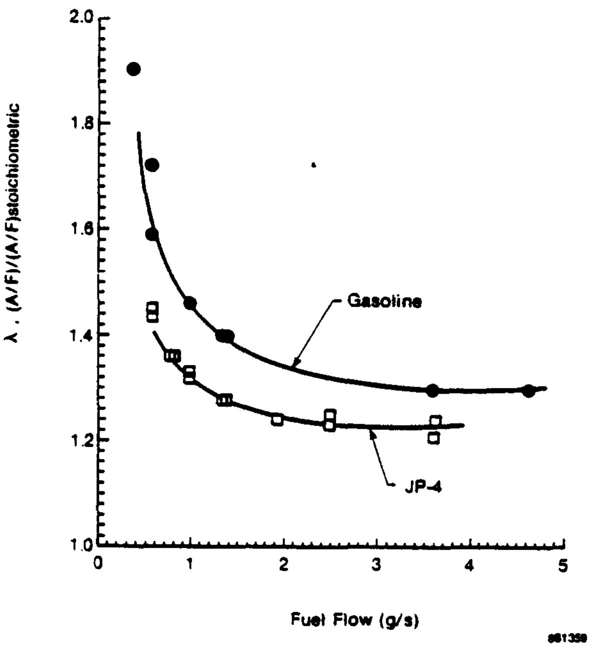

Fig. 6 Bosch K-Jetronic λ Characteristics for the Upgraded Mod I Engine

The effect of fuel type on steady-state performance and start-up was tested using a combustion rig that simulated the engine's external heat system. The actual fuels used are indicated on Table 4. Standard gasoline and JP-4 fuels were used, the latter satisfying the requirements of MIL-T-5624L. However, a blend of DF-2 and gasoline (65/35%) was substituted for the diesel fuel. This blend does not correspond to ASTM 2D specification because the flash point is too low. Therefore, the results may be more optimistic than if DF-2 were used. Test variables included both constant and variable λ as well as 720 and 820°C set temperature*.

Both P-40 and Upgraded Mod I turbulator combustors (Figure 7) were evaluated. Rig results indicated that each would satisfy program goals. P-40 soot emissions are shown in Figure 8; although not shown, Upgraded Mod I results were identical. Since low-flow stability, as evidenced by CO emissions, was superior with the Upgraded Mod I turbulator (Figure 9), it was selected for the van. Ignition tests demonstrated the feasibility of rapid ignition with all three fuels, Figure 10. Ignition delay was defined as the measured time difference between fuel flow and the onset of combustion. Fuel flow was sensed by a pressure transducer at the nozzle, and the onset of combustion was determined by a rise in temperature sensed by thermocouples located in the combustor. The actual chemical ignition delay is much shorter than indicated, since the measurements include time for the fuel to flow through the nozzle and the thermocouple response time.

UPGRADED MOD I ENGINE CHARACTERIZATION FOR THE VAN INSTALLATION

Prior to installation in the van, an Upgraded Mod I engine was installed in MTI's engine dynamometer cell and thoroughly characterized on both unleaded gasoline and JP-4 fuel. The results of that testing, in terms of power output and efficiency, are shown in Figure 11. The curves represent full load at an engine internal charge pressure level of 15 MPa. It should be noted that there is no difference in performance using either fuel. Further, it should be noted that no mechanical or electrical changes or adjustments were made to achieve operation on either fuel.

The engine evaluation also verified combustion rig data and the effect of fuel density changes on λ (see Figure 6). Gaseous emissions, Figure 12, were as expected. The relatively high NO_x levels are due to the lack of recirculated combustion products, e.g., high flame temperature. The NO_x levels could be reduced by exhaust gas recirculation (11) if future needs require this change. NO_x and HC emissions are nearly the same for each fuel. CO appears to be slightly higher with JP-4, which is indicative of larger fuel droplet size. Soot emissions were practically nonexistent (Figure 13); and heater head temperature variation was insensitive to fuel type and within acceptable limits (Figure 14).

During the course of cell testing, numerous starts were made with gasoline and JP-4. Changes were made to the control system to improve JP-4 hot-start capability. This change involved reducing start-up air flow and time at that flow to a more optimum condition, thus enabling consistently reliable starts. Sixty test hours and twenty-seven starts were achieved with the conical nozzle without plugging or degradation in performance.

INSTALLATION OF THE UPGRADED MOD I IN THE VAN

Minor modifications were made prior to installing the engine in the van. The only structural modification was to the front frame crossmember to permit alignment of the engine output shaft to the vehicle drive shaft (Figure 15). The transmission in the baseline diesel-powered van was a vacuum modulated, three-speed automatic. The

*The set temperature is the average of the rear row heater head thermocouples, a prime engine control parameter.

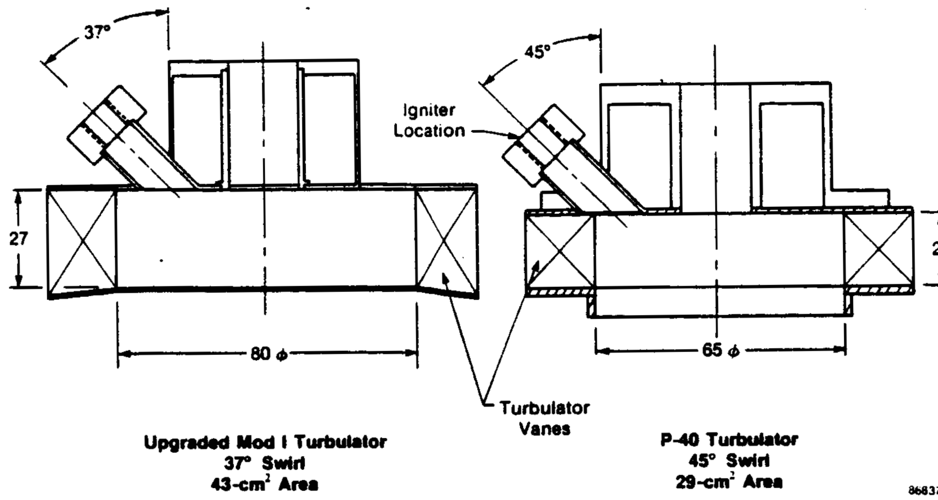

Fig. 7 Comparison of Upgraded Mod I and P-40 Turbulators

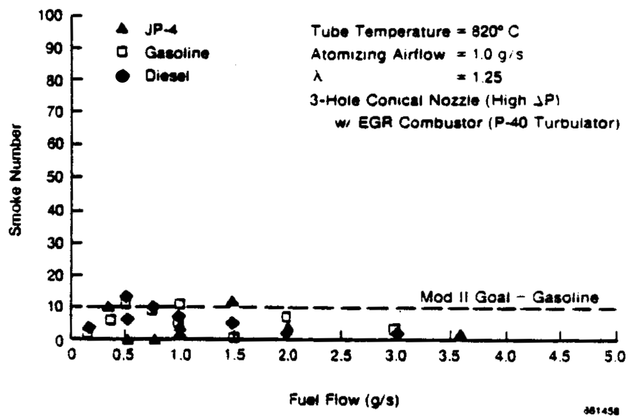

Fig. 8 Effect of Fuel Type on Rig Soot Emissions

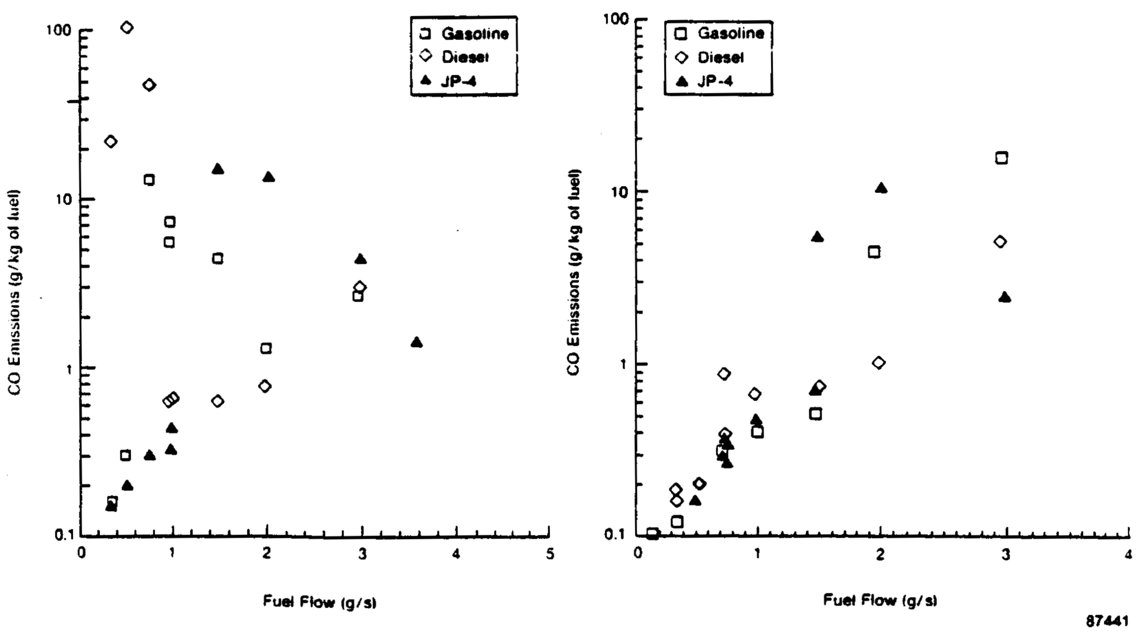

Fig. 9 Effect of Combustor on Rig CO Emissions

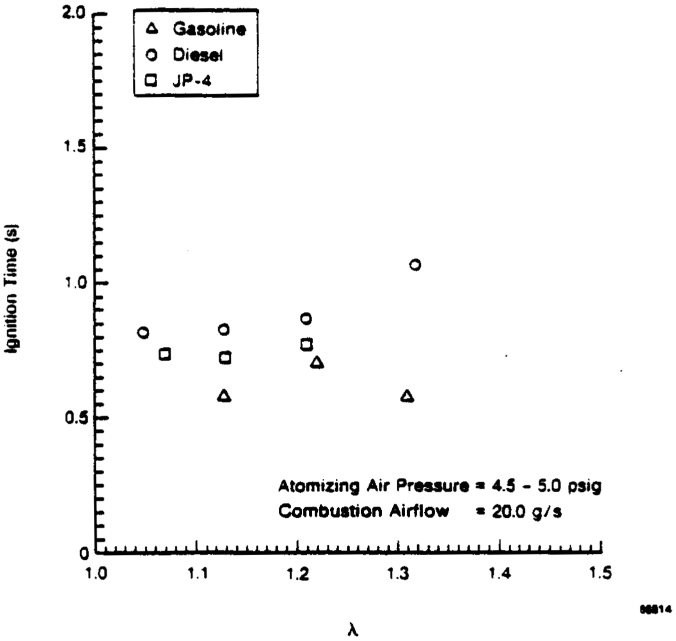

Fig. 10 Combustion Rig Ignition Delay

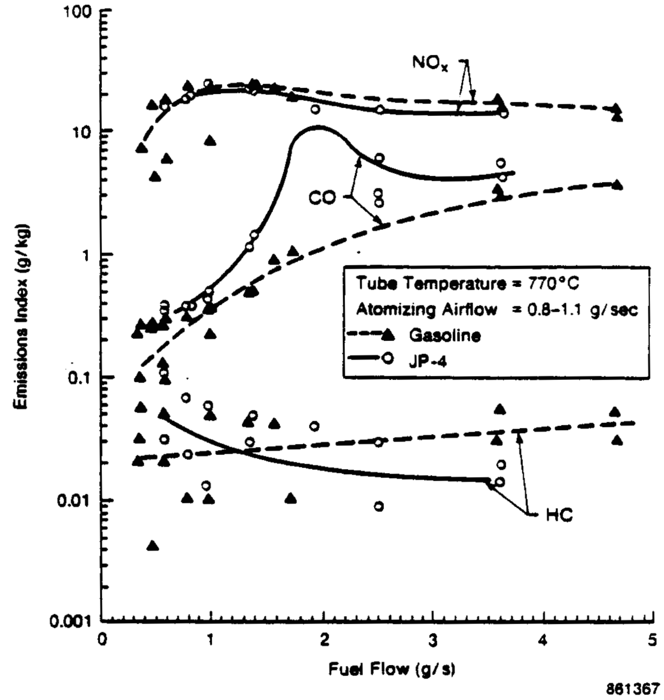

Fig. 12 Upgraded Mod I Engine Emissions

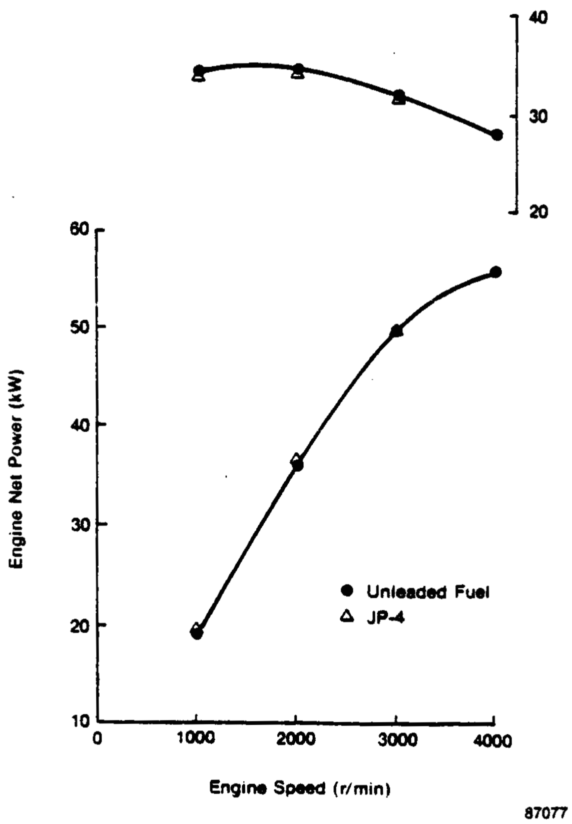

Fig. 11 Upgraded Mod I Performance Using Unleaded Fuel and JP-4

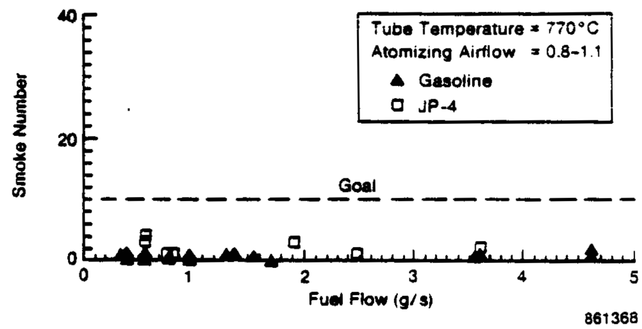

Fig. 13 Upgraded Mod I Engine Soot Emissions

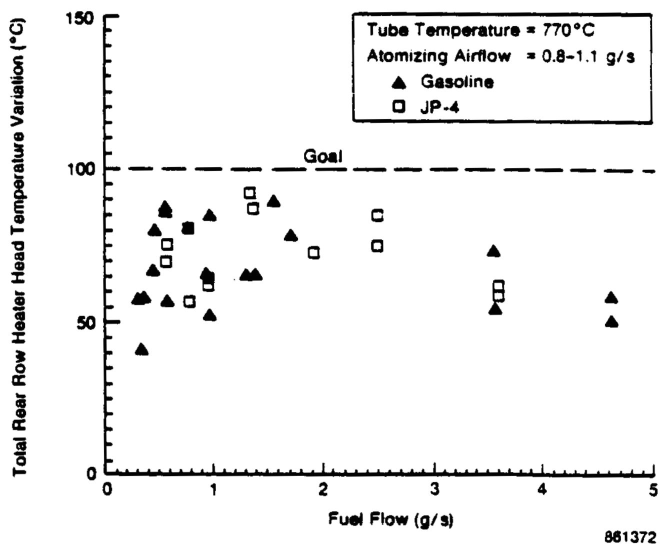

Fig. 14 Upgraded Mod I Engine Heater Head Temperature Variation

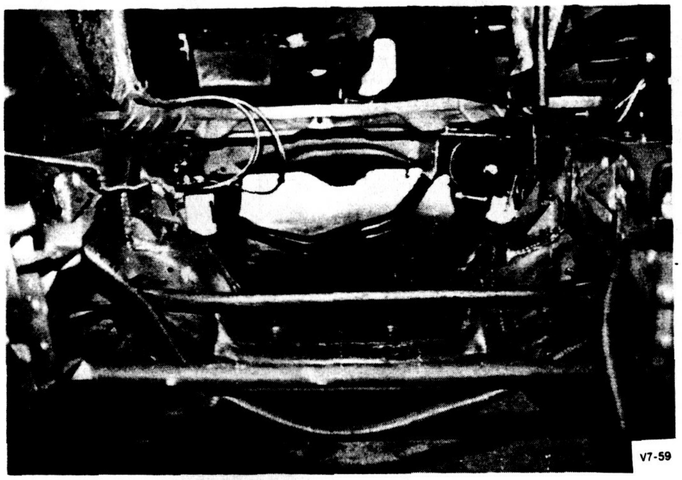

Fig. 15 Front Crossmember Modification

Stirling engine is an external combustion engine and does not have intake manifold vacuum. To match the characteristics of the transmission supplied with the vehicle, a vacuum pump would have to be added to the engine and extensive development performed to match the vacuum signal with the engine operating characteristics. A Chrysler nonvacuum, modulated, 3-speed automatic used extensively in earlier ASE vehicle installations was therefore substituted for the GM transmission.

Changes that would impact the driver were kept to a minimum. From turning the key for starting to keying off at the end of vehicle use, the controls are identical to that of the diesel. A recording device was added to track engine charge pressure and engine and vehicle speed. Instrumentation for engine monitoring, control, and diagnostic purposes was mounted on an overhead panel to the rear of the driver to keep the dashboard simple. See Figure 16.

The Stirling engine runs with water system temperatures considerably lower than internal combustion engines (∽50°C as opposed to ∽100°C). Thus, the increase realized in high efficiency results in water that is not hot enough for passenger compartment heating. Therefore, two gasoline-fired heaters were installed in the van, one for windshield defogging and one for passenger compartment heating. These heaters are used in several automotive installations, including school buses. An auxiliary fuel tank was added to ensure a gasoline supply for these heaters, if another fuel were chosen for main vehicle propulsion.

INITIAL CHECKOUT AND OPERATION IN PHASE I

Operational readiness was evaluated by driving the vehicle over the road, as well as by simulating expected Air Force driving on MTI's vehicle dynamometer. Acceleration from 0 to 30 mph was conducted to verify engine health; the average was 10.5 seconds which coincided with the acceleration predicted by the MTI vehicle simulation code. A total of 52 hours of operation was accumulated prior to delivery to the Air Force, which included approximately nine hours and five starts using JP-4 fuel.

The van is currently in use at Langley Air Force Base to transport aircraft maintenance personnel to and from the planes they service. The operational experience accumulated in Phase I on unleaded fuel is summarized in Figure 17. This experience is considered quite good for an engine still in the prototype stage and compares favorably with operational experience with diesel-powered vans.

Fig. 16 Stirling Engine Monitoring Panel Installed Behind Driver

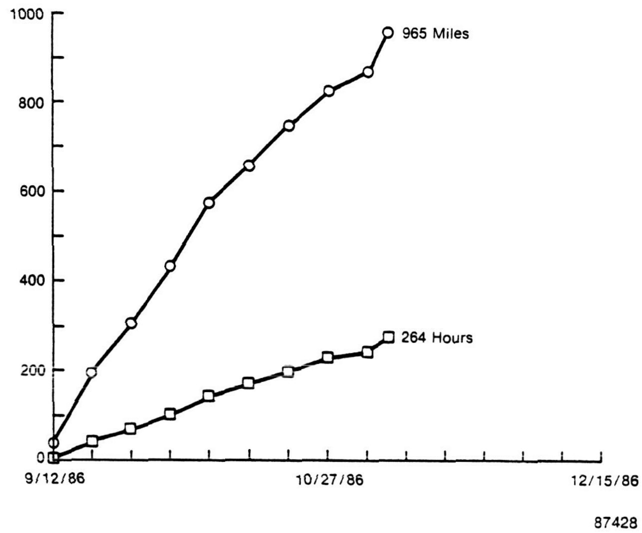

Fig. 17 Stirling-Powered Air Force Van Operational Experience

SUMMARY AND CONCLUSIONS

The rig and engine tests demonstrated start-up capability and steady-state operation on gasoline, JP-4, and diesel fuel, while satisfying all program goals. Limited testing did not reveal any detrimental effects on engine durability following operation on JP-4 fuel.

The installation and initial operational experience with the Air Force van provides proof-of-concept readiness for this application. It is anticipated that expanded capabilities will be demonstrated in the alternative fuels and environmental extremes testing to be conducted in Phase II of this program. Installations of the Upgraded Mod I and the Mod II engines in vehicles better suited to the engine's power output will provide final demonstration of the Stirling engine's capability.

ACKNOWLEDGMENT

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REFERENCES

1. MTI, "Assessment of the State of Technology of Automotive Stirling Engines," DOE/NASA Report 0032-79/4, September 1979.
2. Haaland, Yngve, "The Automotive Mod I Stirling Engine," United Stirling (Sweden) AB, Proceedings of the 19th Automotive Technology Development Contractor's Coordination Meeting, Nineteenth Summary Report, October 1981.
3. Moodysson, Bengt-Ove, "Upgraded Mod I Stirling Engine Design," United Stirling (Sweden) AB, Proceedings of the 20th Automotive Technology Development Contractor's Coordination Meeting, Nineteenth Summary Report, October 1982.
4. MTI, "ASE Development Program Mod II Stirling Engine System (BSE) Design Review Report," MTI 85TR24, April 1985.
5. MTI, "ASE Development Program Mod II Stirling Engine System (SES) Design Review Report," MTI 85TR47, August 1985.
6. Battista, R. A., "Stirling Engine Alternative Fuels Test Results," Proceedings of the 20th Automotive Technology Development Contractor's Coordination Meeting, Dearborn, Michigan, SAE P120, October 1982.
7. Battista, R. A., and Connelly, M., "Evaluation of Alternate Fuels: Performance in an External Combustion System," DOE Report No. DOE/CE/50043-1, December 1985.
8. Shaltens, R., "Stirling Powered Van Program Overview," DOE/NASA Report 50112-62, February 1986.
9. Odgers, J., and Kretschmer, D., "The Prediction of Thermal NO_x in Gas Turbines," ASME Paper 85-IGT-126, September 1985.
10. Lefebvre, A. H., "Gas Turbine Combustion," New York: McGraw-Hill, 1983.
11. Farrell, R. A., "Mod I Stirling Engine Emissions with Exhaust Gas Recirculation," Proceedings of the 20th Automotive Technology Development Contractor's Coordination Meeting, SAE P120, Dearborn, Michigan, October 1982.
12. Ernst, W. et al., "Automotive Stirling Engine Development Program Semiannual Technical Progress Report for Period July through December 1985," DOE/NASA Report No. DOE/NASA/0032-27, May 1986.